Dark Matter and Electroweak Baryogenesis in the MSSM

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Based on works done in collaboration with
M. Quiros and C. Wagner, Phys.Lett.B380:81-91,1996; Nucl.Phys.B524:3-22 (1998)
C. Balazs and C Wagner, Phys. Rev. D70: 035003 (2004)
C. Balazs, A. Menon, D. Morrissey and C. Wagner, PRD71, 075002 (2005)
A. Finch, A Freitas, C. Milstene, H. Nowak and A. Sopczak, in preparation

Outline

- Cosmology as Motivation for Physics BSM
  -- Dark Matter -- the Baryon Asymmetry
- Electroweak Baryogenesis in the MSSM
  -- Necessary requirements for EWBG
  -- Constraints on the SUSY spectrum
- Dark Matter in the MSSM
  -- Dark Matter in the presence of EWBG
  -- Collider Signatures
  -- Direct DM detection and the effects of CP violation
- Conclusions

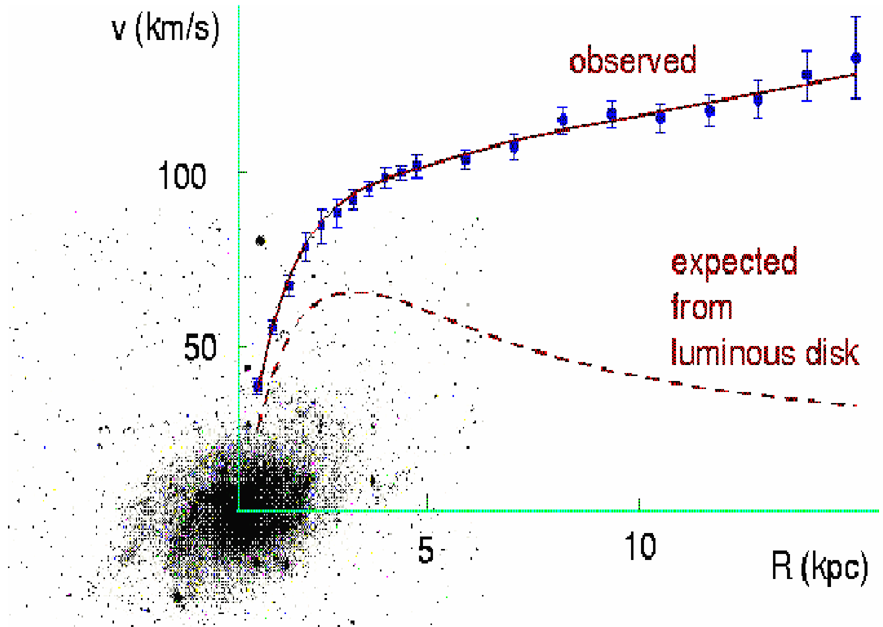
Evidence for Dark Matter:

- Rotation curves from Galaxies.
- Gravitational Lensing.
- Simulations of structure formation.
- Anisotropies in the CMB radiation.

Strong evidence for additional, non-luminous, source of matter:

Dark Matter

Gravity Prediction: $\frac{v^2}{r} = G_N \frac{M(r)}{r^2} \Rightarrow v^2 \propto \frac{1}{r}$



WMAP measures the CMB and determines :

$\Omega_M h^2 = 0.135 \pm 0.009$ $\Omega_B h^2 = 0.0224 \pm 0.0009$ $h = 0.71 \pm 0.04$

difference gives CDM energy density: $\Omega_{CDM}\, h^2 = 0.1126 \pm^{0.0161}_{0.0181}$

Possible origin of Dark Matter:

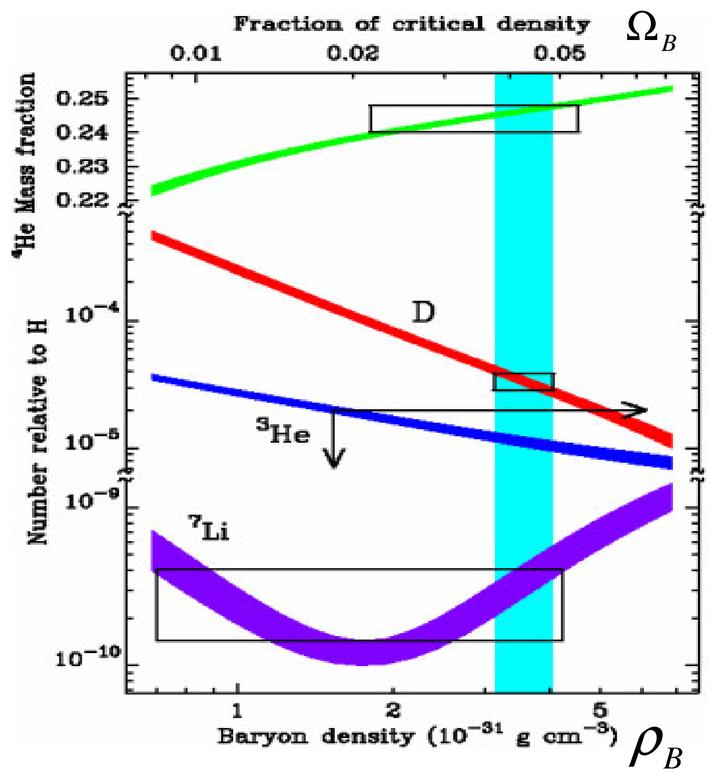
Weakly interacting particles (WIMPS), with masses and interaction cross sections of order of the electroweak scale

- **The SM has no suitable candidate**

The Puzzle of the Matter-Antimatter asymmetry

- Anti-matter is governed by the same interactions as matter.
- Observable Universe is mostly made of matter: $N_B >> N_{\bar{B}}$
- Anti-matter only seen in cosmic rays and particle physics accelerators
  The rate observed in cosmic rays consistent with secondary emission of antiprotons $N_{\bar{P}} \approx 10^{-4} \ N_P$

Information on the baryon abundance:



- Abundance of primordial elements combined with predictions from Big Bang Nucleosynthesis:

$$\eta = \frac{n_B}{n_\gamma}, \quad n_\gamma = \frac{421}{cm^3}$$

- CMBR:

$$\frac{\rho_B}{\rho_c} \equiv \Omega_B, \qquad \rho_c \approx 10^{-5} h^2 \frac{GeV}{cm^3}$$

Baryon-Antibaryon asymmetry

- Baryon Number abundance is only a tiny fraction of other relativistic species

$$\eta = \frac{n_B}{n_\gamma} = 2.68\ 10^{-8}\,\Omega_B h^2 \approx 6\ 10^{-10}$$

- In early universe $B, \bar{B}$ and γ's were equally abundant. $B, \bar{B}$ annihilated very efficiently. No net baryon number if B would be conserved at all times.

What generated the small observed baryon--antibaryon asymmetry ?

Sakharov's Requirements:

- Baryon Number Violation (any B conserving process: $N_B = N_{\bar{B}}$)
- C and CP Violation: $(N_B)_{L,R} \neq (N_{\bar{B}})_{L,R}$
- Departure from thermal equilibrium

All three requirements fulfilled in the SM

In the SM Baryon Number conserved at classical level but violated at quantum level : $\Delta B = \Delta L$

Anomalous processes violate both B and L number, but preserve B-L. (Important for leptogenesis idea)

- *At T = 0, Baryon number violating processes exponentially suppressed*

$$\Gamma_{\Delta B \neq 0} \cong \exp(-2\pi / \alpha_{\mathrm{W}})$$

- *At very high temperatures they are highly unsuppressed,*

$$\Gamma_{\Delta B \neq 0} \propto T$$

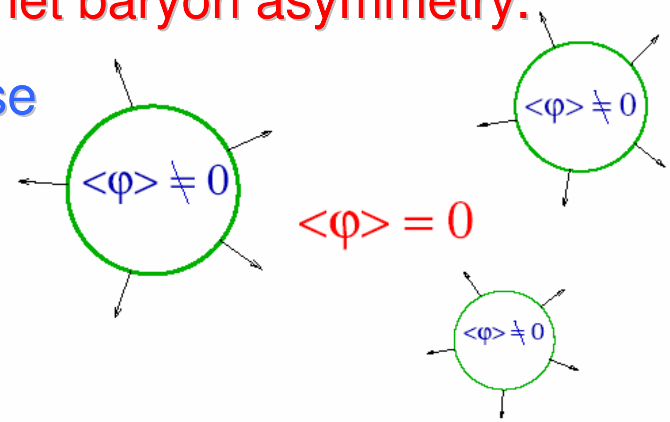
- *At Finite Temperature, instead, only Boltzman suppressed*

$$\Gamma_{\Delta B \neq 0} \cong \beta_0 \, \mathrm{T} \exp(-\mathrm{E}_{\mathrm{sph}}(\mathrm{T}) / \mathrm{T})$$

with $\mathrm{E}_{\mathrm{sph}} \cong 8\pi \, \mathrm{v(T)} / \mathrm{g}$ and v(T) the Higgs v.e.v.

Baryogenesis at the Electroweak Phase transition

- Start with B=L=0   at T>Tc
- CP violating phases create chiral baryon-antibaryon asymmetry in the symmetric phase. Sphaleron processes create net baryon asymmetry.
- Net Baryon Number diffuse in the broken phase



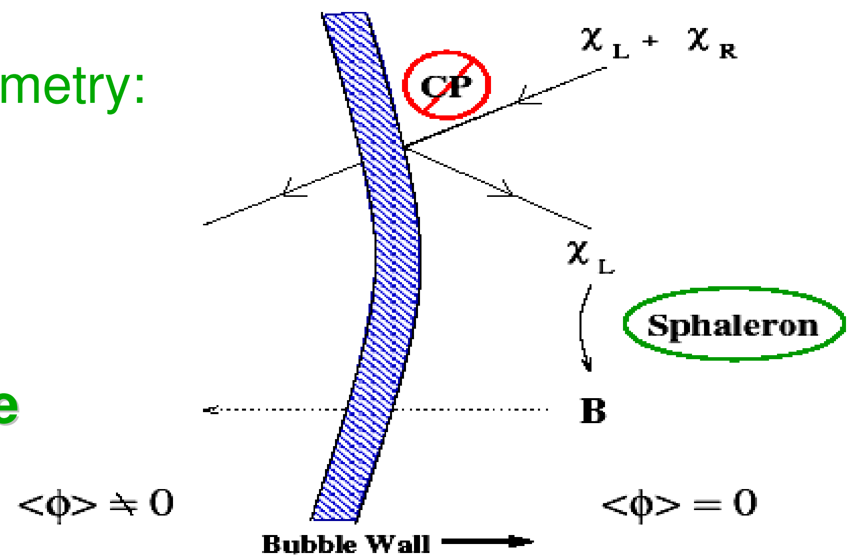
if $n_{\mathbf{B}} = 0$ at T > Tc, independently of the source of baryon asymmetry

$$\frac{n_B}{s} = \frac{n_B(T_c)}{s}\exp\left(-\frac{10^{16}}{\mathrm{T_c(GeV)}}\exp\left(-\frac{\mathrm{E_{sph}(T_c)}}{\mathrm{T_c}}\right)\right)$$

To preserve the generated baryon asymmetry:
strong first order phase transition:

$$v(T_c)/T_c > 1$$

Baryon number violating processes out of equilibrium in the broken phase



SM Electroweak Baryogenesis fufills the Sakharov conditions

- **SM Baryon number violation: Anomalous Processes**
- **CP violation: Quark CKM mixing**
- **Non-equilibrium: Possible at the electroweak phase transition.**

Finite Temperature Higgs Potential

$$V = D\,(T^2 - T_0^2)\,H^2 + E_{SM}\,T\,H^3 + \lambda(T)\,H^4$$

E receives contributions proportional to the sum of the cube of all light boson particle masses and

$$\frac{v(T_c)}{T_c} \approx \frac{E}{\lambda} \quad , \quad \text{with} \quad \lambda \propto \frac{m_H^2}{v^2}$$

Since in the SM the only bosons are the gauge bosons, and the quartic coupling is proportional to the square of the Higgs mass

$$\frac{v(T_c)}{T_c} > 1 \quad \text{implies} \quad m_H < 40\ \text{GeV} \Rightarrow \text{ruled out!}$$

- **Independent Problem: not enough CP violation**

Electroweak Baryogenesis in the SM is ruled out

Supersymmetry and Cosmology

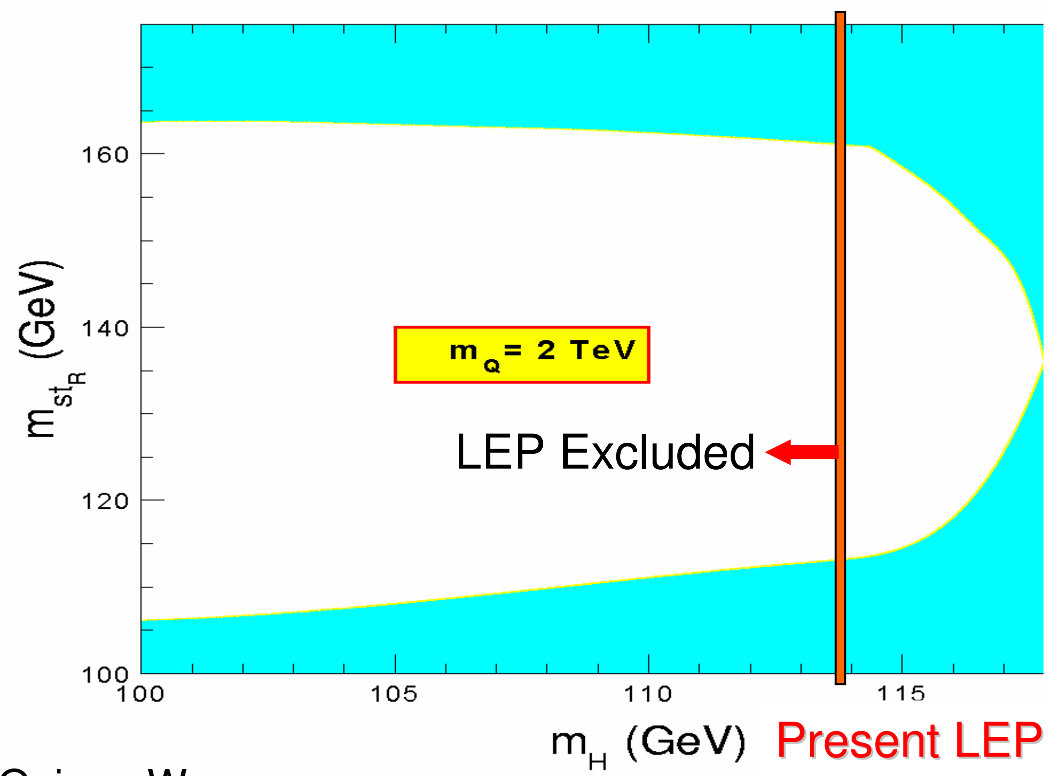
- SUSY is well motivated on purely particle physics grounds.
  The minimal SUSY extension of the SM leads to:
  - stabilization of the electroweak scale.
  - unification of gauge couplings.
- The MSSM also helps with cosmology.
- Dark Matter:
  - The lightest SUSY particle (LSP) is stable because of R-parity.
  - If the LSP is a neutralino, it can account for the dark matter.
- Baryon Asymmetry:
  - New CP violating phases can arise when SUSY is softly broken.
  - The baryon asymmetry can be generated within the MSSM by the mechanism of electroweak baryogenesis.
- Can the MSSM explain both simultaneously?

In the MSSM:

- New bosonic degrees of freedom: superpartners of the top quark, with strong couplings to the Higgs. $\Rightarrow E_{SUSY} \approx 8\, E_{SM}$

Suficciently strong first order phase transition to preserve generated baryon asymmetry:

- ***Higgs masses up to 120 GeV***
- ***The lightest stop must have a mass below the top quark mass.***

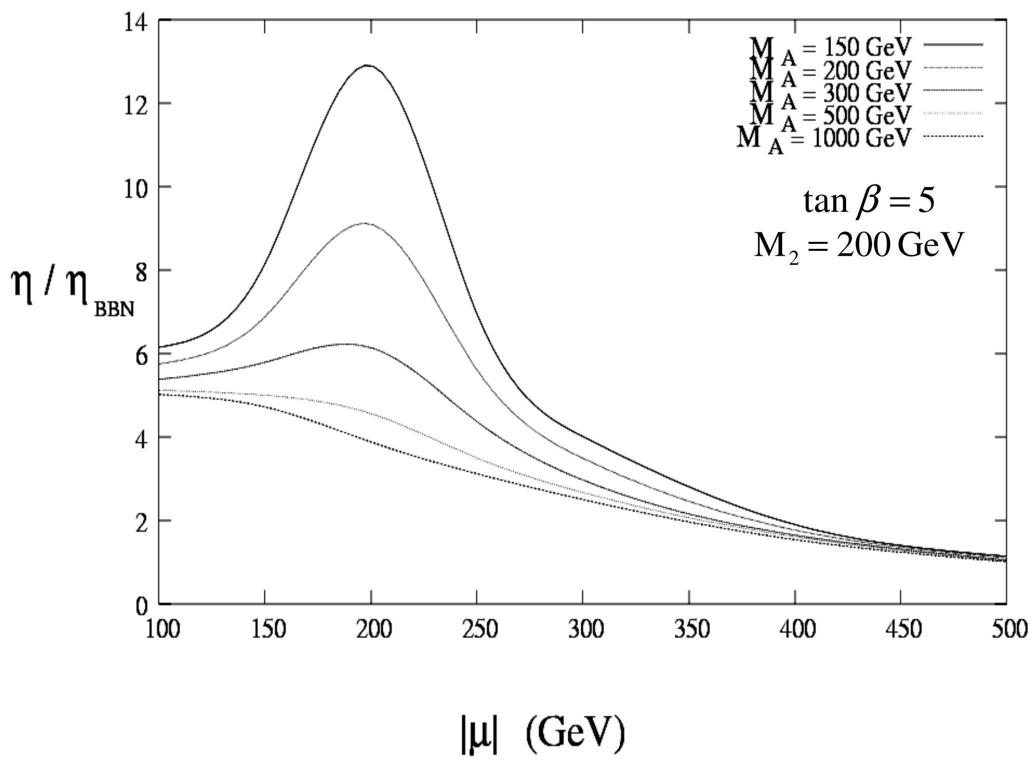


M.C, Quiros, Wagner

Present LEP bounds on the SM- like Higgs mass $m_{H_{SM-like}} > 114.6\,\text{GeV}$

Baryon Asymmetry Dependence on the Chargino Mass Parameters

M.C., M.Quiros,M. Seco and C. Wagner 02



- **New CP violating Phases are crucial**

Results for maximal CP violation

$$\sin(\arg(\mu^* M_2)) = 1$$

- Gaugino and Higgsino masses of the order of the weak scale highly preferred

- Results scale with $\sin(\arg(\mu^* M_2))$ and (approx) with $\sin 2\beta$

Baryon Asymmetry Enhanced for ***;*** $M_2 = |\mu|$ ***and smaller values of*** m_A

Even for large values of the CP-odd Higgs mass, acceptable values obtained for phases of order one.

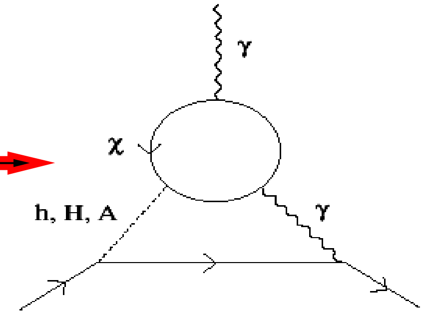
Phases in the MSSM EWBG scenario very constrained by EDM limits

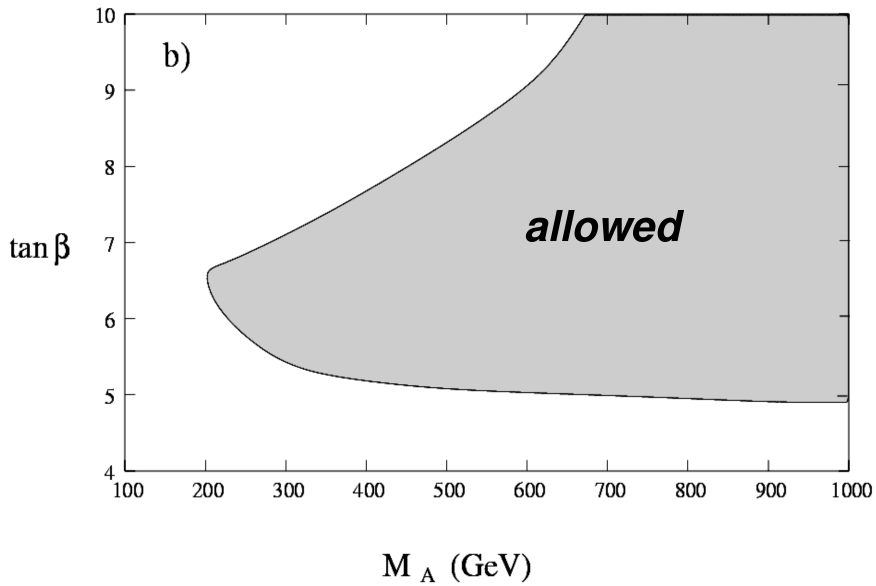
- One loop contributions become negligible for

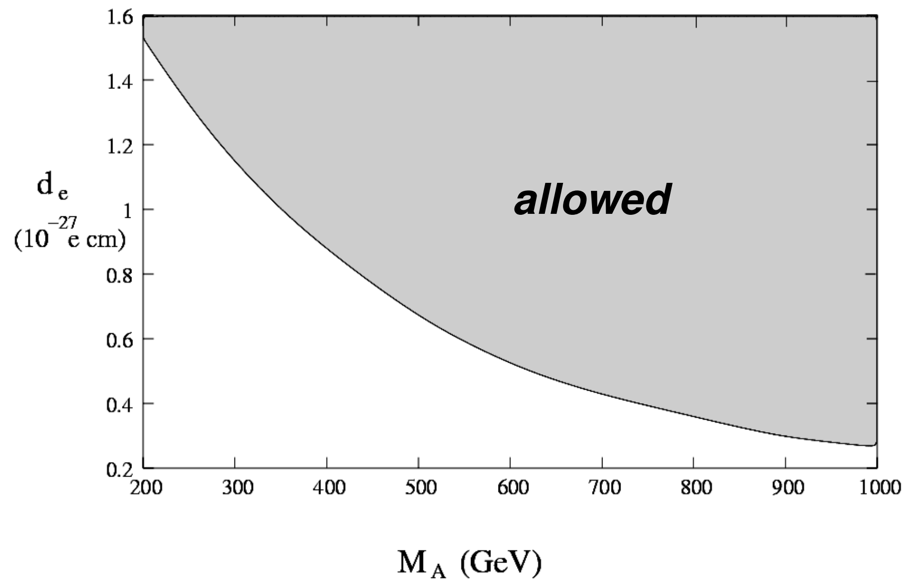
$$m_{\tilde{f}_{1,2}} \geq 10\,\text{TeV}$$

- At two loop order contributions from virtual charginos and Higgs bosons, proportional to

$$\sin(\arg(\mu^* M_2))$$





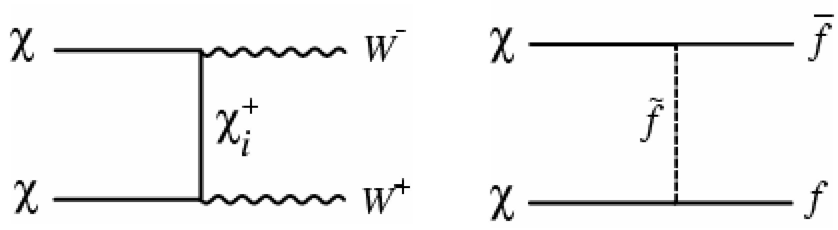


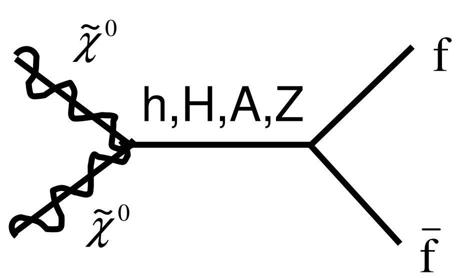
$$\Rightarrow 5 \leq \tan\beta \leq 10 \qquad M_A \geq 200\,\text{GeV} \qquad 110\,\text{GeV} \leq |\mu| \leq 550\,\text{GeV (not shown)}$$

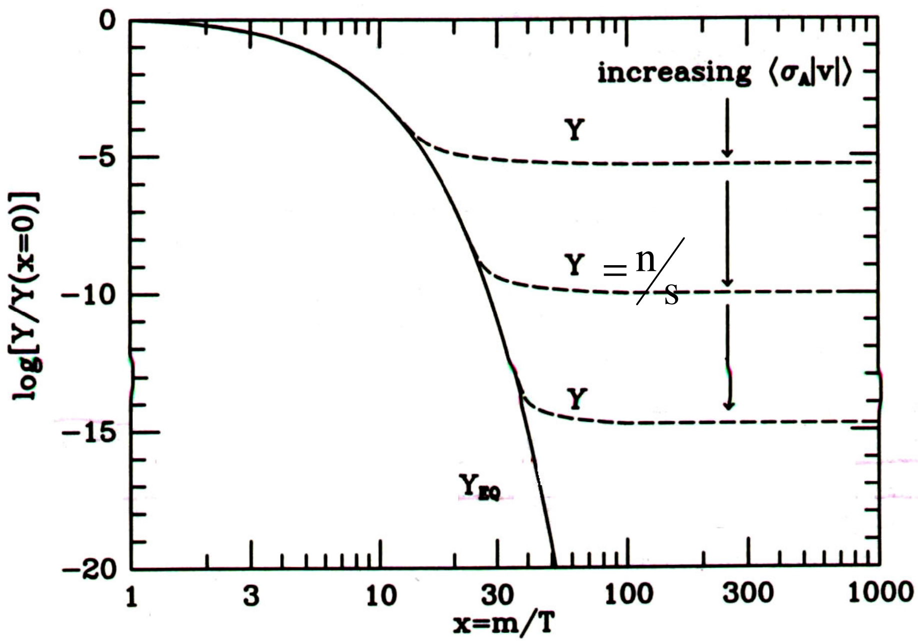
- An order of magnitude improvement in the electron EDM over the present bound $|d_e| < 1.6\times 10^{-27}\,\text{e cm}$, will leave little room for this scenario (uncertainties of O(1)!), or demand specific cancellations between one and two loop contributions.

Dark Matter in the MSSM

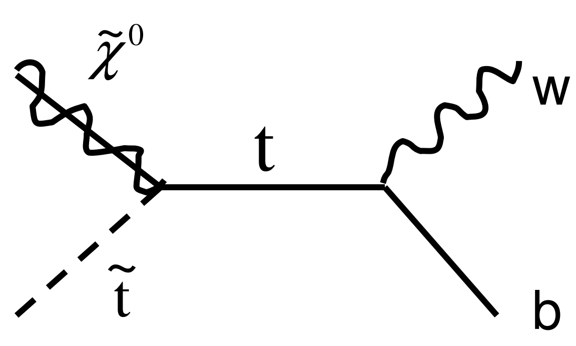
Relic density is inversely proportional to the thermally averaged $\tilde{\chi}^0 \tilde{\chi}^0$ annihilation cross section $\langle \sigma \, \mathrm{v} \rangle$

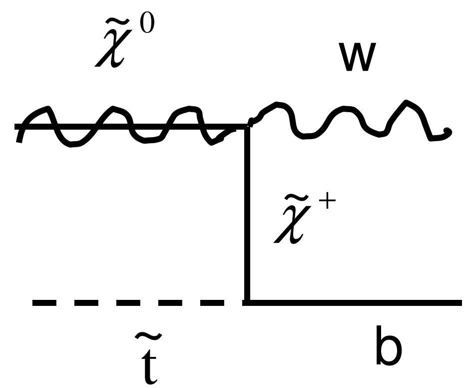






If any other SUSY particle has mass close to the neutralino LSP, it may substantially affect the relic density via co-annihilation





if stops NLSP

neutralino-stop

co-annihilation

Dark Matter and Electroweak Baryogenesis

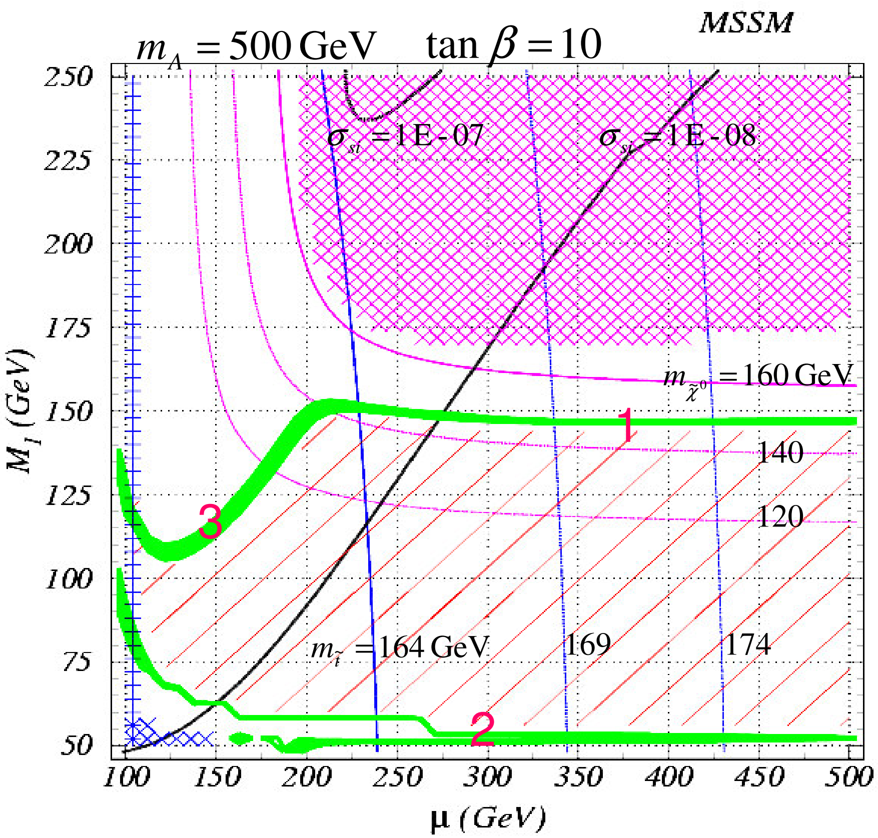
EWBG conditions, Higgs and EDM bounds

- light right handed stop: $m^2_{\tilde{U}_3} \leq 0$ • heavy left handed stop: $m^2_{\tilde{Q}_3} \geq (1\,\mathrm{TeV})^2$
- values of stop mixing compatible with Higgs mass constraints and with a strong first order phase transition: $|X_t| = |A_t - \mu^* / \tan\beta| = 0.3 - 0.5\,\mathrm{m}_{\tilde{\mathrm{Q}}_3}$
- light charginos with $\mu, \mathrm{M}_2 \leq 500\,\mathrm{GeV}$
- large CP violating phases in the chargino sector $\sin(\arg(\mu^* \mathrm{M}_2)) \geq 0.1$
- $5 \leq \tan\beta \leq 10$ $\mathrm{M}_\mathrm{A} \geq 200\,\mathrm{GeV}$
- the rest of the squarks, sleptons and gluinos heavy

Implications for Dark Matter:

- Neutralino LSP must be lighter that the stop. If they are close in mass, coannihilation greatly reduces the relic density
- If $m_{\tilde{\chi}^0} \cong m_h/2$, neutralino annihilation enhanced by s-channel h resonance
- CP phases in the chargino sector affect the mass and couplings of the LSP

Relic Density Computation



Balazs, MC, Wagner 04; Balazcs, MC, Menon, Morrissey, Wagner 04 (w/CP phases)

three interesting regions with neutralino relic density compatible with WMAP obs.

$0.095 < \Omega_{\text{CDM}} h^2 < 0.129$ (green areas)

1. neutralino-stop co-annihilation: mass difference about 20-30 GeV

2. s-channel neutralino annihilation via lightest CP-even Higgs

3. annihilation via Z boson exchange small μ and M_1

- Similar qualitative results under variations in the phase of mu
- Some differences arise in the h resonance region due to variations in the imaginary part of the $\tilde{\chi}^0\tilde{\chi}^0 h$ couplings.
- The $\tilde{\chi}^0 t\,\tilde{t}$ coupling varies somewhat with the phase but the main effect is due to the variation of the LSP mass which affects the co-annihilation contribution.

Experimental Tests of Electroweak Baryogenesis and Dark Matter

- Higgs searches:

Higgs associated with electroweak symmetry breaking: SM-like.
Higgs mass below 120 GeV required

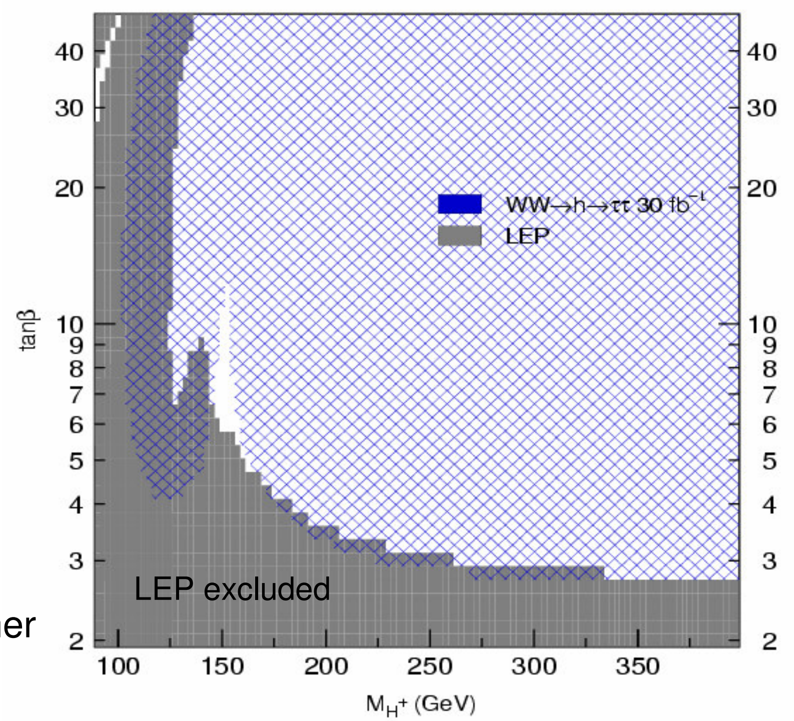
1. Tevatron collider may test this possibility: 3 sigma evidence with about 4 fb^{-1}

Discovery quite challenging, detecting a signal will mean that the Higgs has relevant strong (SM-like) couplings to W and Z

2. A definitive test of this scenario will come at the LHC with the first 30 fb^{-1} of data

$$qq \rightarrow qqV^*V^* \rightarrow qqh$$
$$\text{with } h \rightarrow \tau^+\tau^-$$

Maximal mixing scenario



M.C, Mrenna, Wagner

Searches for a light stop at the Tevatron

Light-stop models with neutralino LSP dark matter $\longrightarrow$ $\not{E}_T$ signal

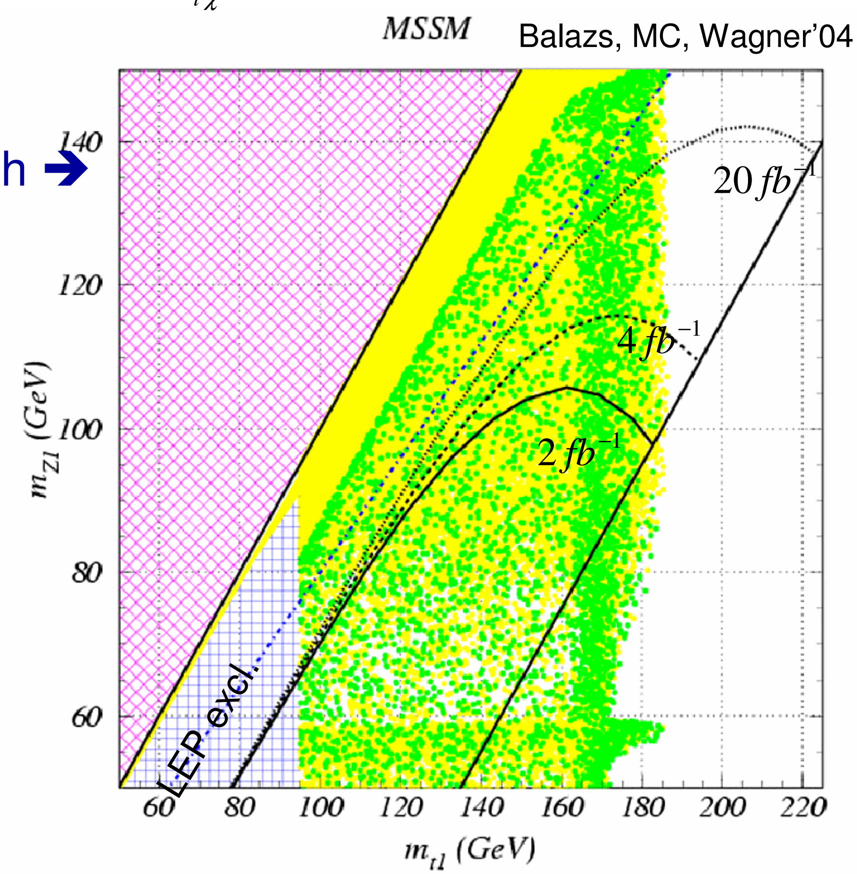
- if $\tilde{t} \longrightarrow c\tilde{\chi}$ decay mode dominant and $\Delta_{m_{\tilde{t}\tilde{\chi}}} < 30$ GeV:

  trigger on $\not{E}_T$ crucial

$m_{\tilde{\chi}^0} < 100\,\mathrm{GeV}$ and $m_{\tilde{t}} \leq 180\,\mathrm{GeV}$ at reach if $\Delta_{m_{\tilde{t}\tilde{\chi}}} \geq 30\,\mathrm{GeV}$

$m_{\tilde{\chi}^0} \geq 120\,\mathrm{GeV}$ then $m_{\tilde{t}}$ out of reach

- co-annihilation region not at Tevatron reach ➔
- away from it strong dependence on the neutralino mass



- if $m_{\tilde{t}} > m_{\tilde{\chi}} + m_W + m_b$ (3-body decay)

this always happens for $m_{\tilde{\chi}^0} \approx m_h/2$

(h-resonance)

and $m_{\tilde{t}} \geq 140\,\mathrm{GeV}$ ➔ no reach

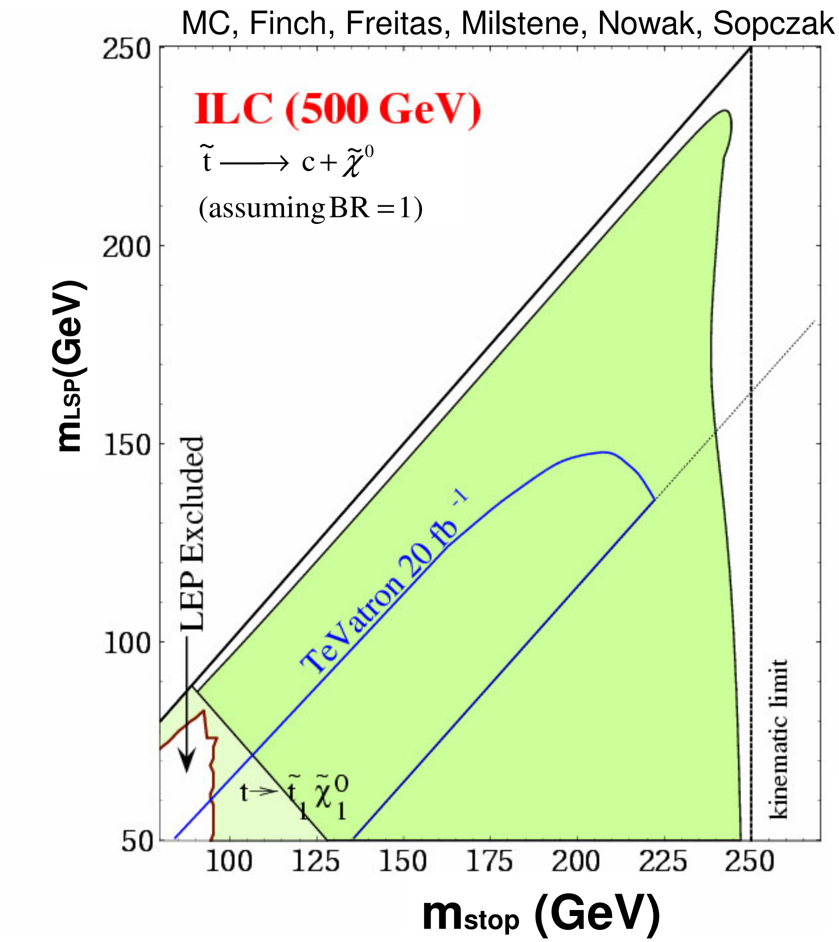
(can search for charginos in trilepton channel)

LHC: quite difficult

(may be in gluino→t stop decays)

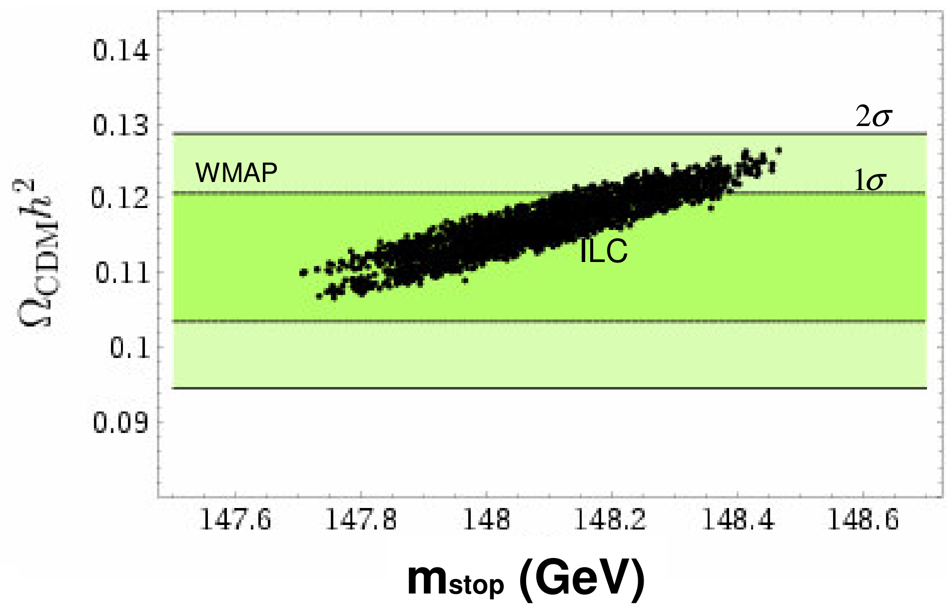
The power of the ILC

- Detect light stop in the whole regime compatible with DM and EWBG



- Measurement of SUSY parameters for Dark Matter density computation

-- stop mass and mixing angles
-- LSP mass and composition
-- Higgs properties
-- other relevant light SUSY particles

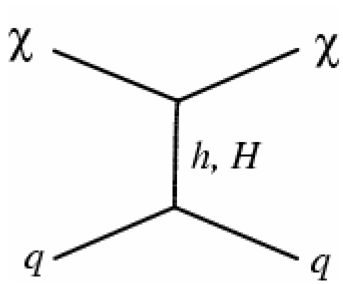


A particle physics understanding of cosmological questions!

Direct Dark Matter Detection

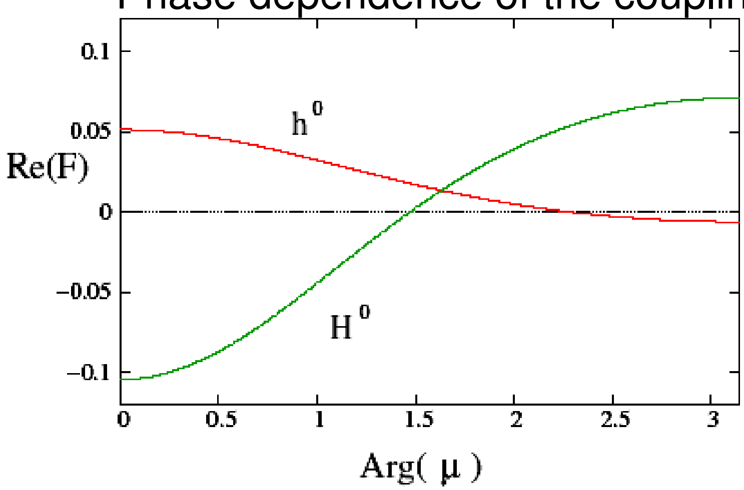
$\not{E}_T$ at colliders ⟶ important evidence of DM candidate,
but, stability of LSP on DM time scales cannot be chekced at colliders

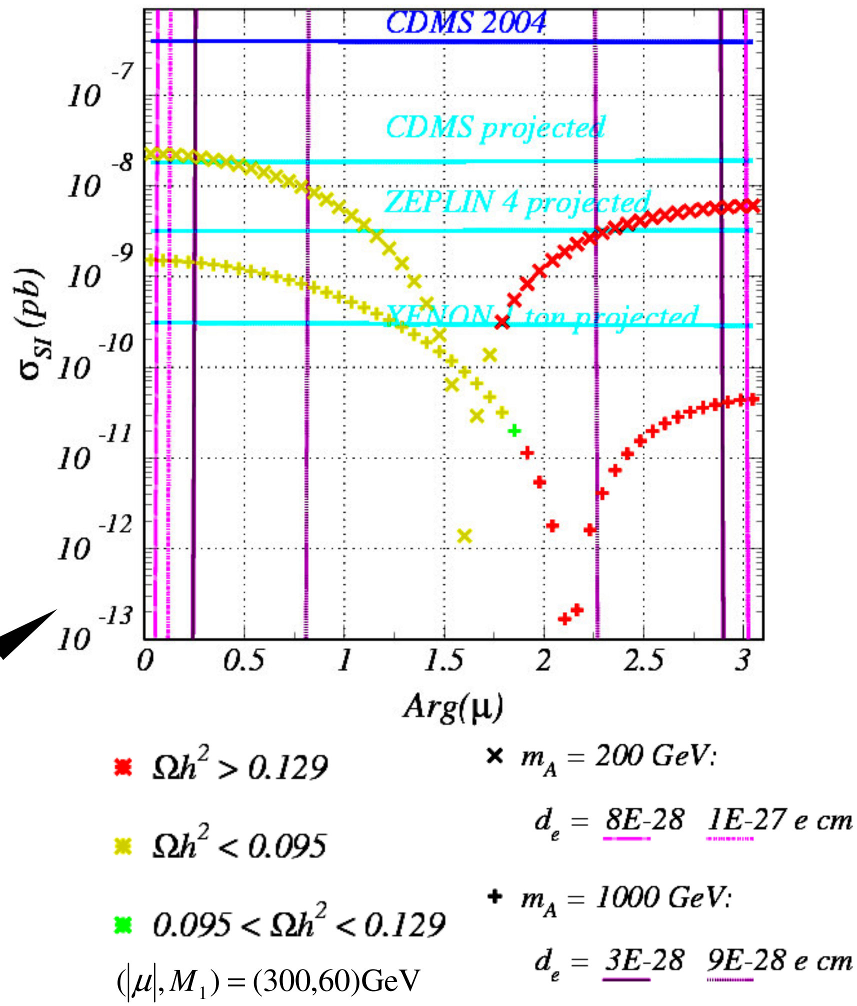
- Neutralino DM is searched for in neutralino-nucleon scattering exp. detecting elastic recoil off nuclei



Only scalar (real) part of $\tilde{\chi}^0\tilde{\chi}^0 h/H$ couplings relevant

Phase dependence of the couplings





Balazs, MC, Menon,Morrissey,Wagner '04

Conclusions

- **Supersymmetry with a light stop** $m_{stop} < m_{top}$ **and a SM-like Higgs with** $m_h < 120$ GeV

↓

opens the window for electroweak baryogenesis and allows for a new region of SUSY parameter space compatible with Dark Matter

also Gaugino and higssino masses of order of the electroweak scale and moderate CP-odd Higgs mass preferred

EWBG and DM in the MSSM → interesting experimental framework

stop-neutralino co-annihilation → challenging for hadron colliders

Tevatron: good prospects in searching for a light stop

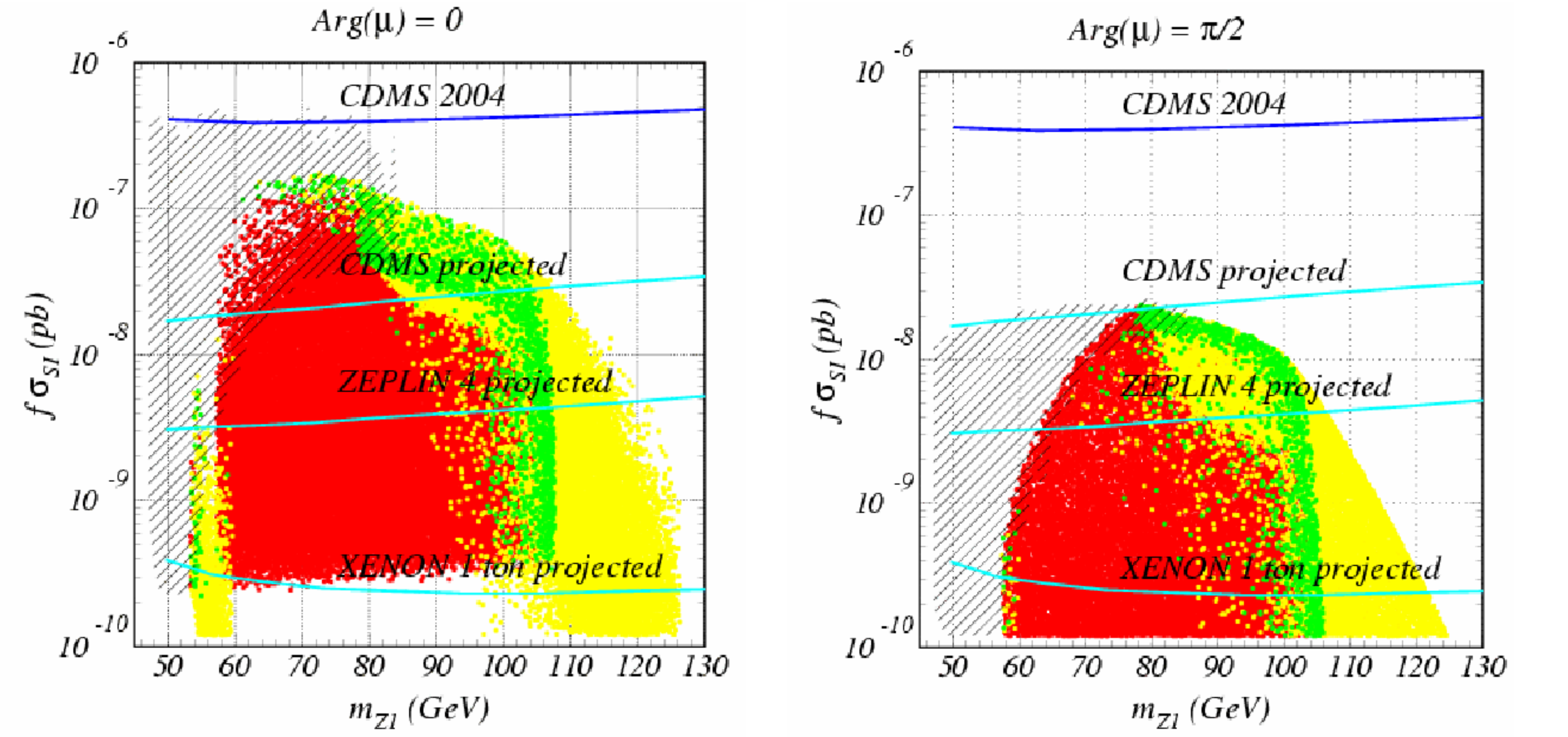
LHC: will add to these searches and explore the relevant $\tilde{\chi}^0$ / $\tilde{\chi}^{\pm}$ *spectra*

Stop co-annihilation region provides motivation to search in the small $\Delta_{m_{\tilde{t}\tilde{\chi}}}$ regime

LC: important role in testing this scenario: small $\Delta_{m_{\tilde{t}\tilde{\chi}}}$ *and nature and composition of light gauginos and stop*

Direct Dark Matter detection: nicely complementary to collider searches

Spin Independent Neutralino-proton scattering cross sections as a function of the neutralino mass for $Arg(\mu) = 0$ and $\pi/2$



small σ_{si} for large μ : co-annihilation and h-resonant regions

Tevatron → LHC → ILC

Windows on to the mysteries of Dark Matter and Baryogenesis

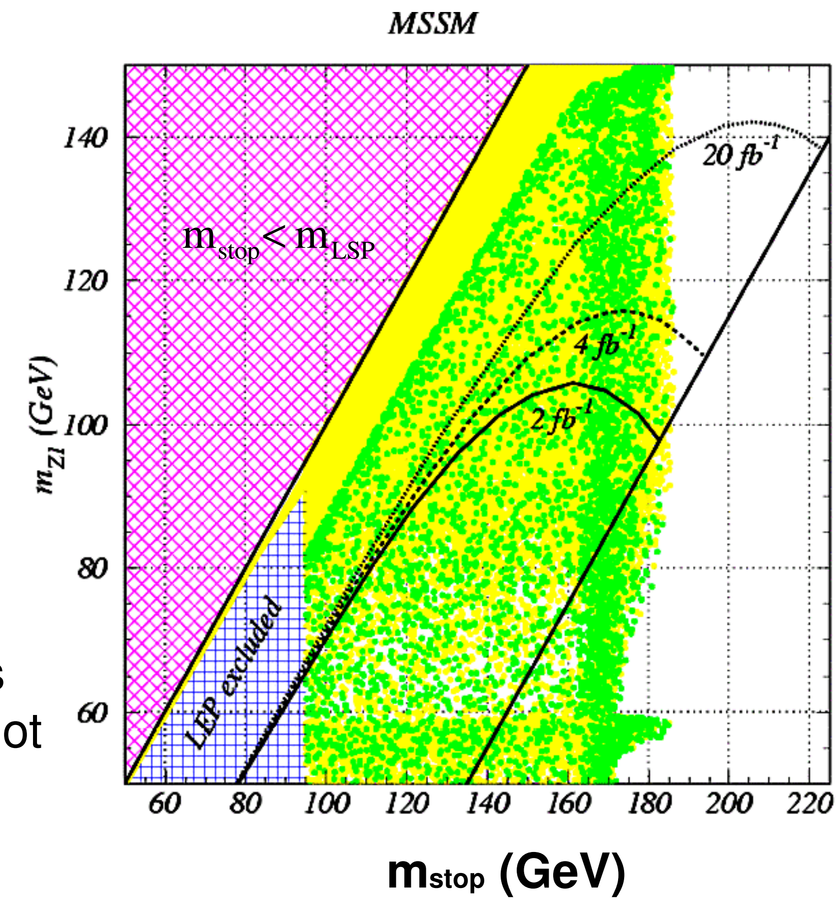
Supersymmetry with a light Higgs $m_h < 120\ \text{GeV}$ **and a light scalar top (stop,** $\tilde{t}$**)** $m_{stop} < m_{top}$ **provides the necessary ingredients**

Lightest Supersymmetric Particle (LSP) ➔ good dark matter candidate

Figure shows Tevatron reach:
Green dots show area consistent with WMAP Dark Matter density determination and with Electroweak Baryogenesis

Good News: light stop can be discovered at CDF and D0 via $\tilde{t} \longrightarrow \text{jet+LSP}$ decays.

Bad News: searches are challenging for hadron colliders when m_{stop} close to m_{LSP} due to soft jets signature. Region of parameters consistent with cosmological observations cannot be fully tested at hadron colliders.



Baryogenesis at the Electroweak Phase transition

- Start with B=L=0 at T>Tc
- CP violating phases create chiral baryon-antibaryon asymmetry in the symmetric phase. Sphaleron processes create net baryon asymmetry.
- Net Baryon Number diffuse in the broken phase

if $n_{\mathbf{B}} = 0$ at T > Tc, independently of the source of baryon asymmetry

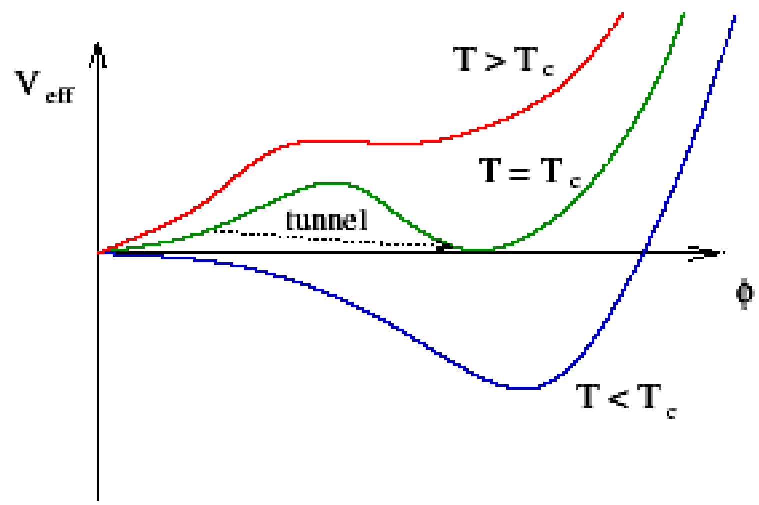
$$\frac{n_B}{s} = \frac{n_B(T_c)}{s} \exp\left(-\frac{10^{16}}{\mathrm{T_c(GeV)}} \exp\left(-\frac{\mathrm{E_{sph}}(\mathrm{T_c})}{\mathrm{T_c}}\right)\right)$$

To preserve the generated baryon asymmetry:

strong first order phase transiton:

$$\mathrm{v}\,(T_c)\,/\,T_c \;>\; 1$$

Baryon number violating processes out of equilibrium in the broken phase



SM Electroweak Baryogenesis fufills the Sakharov conditions

- **Baryon number violation: Anomalous Processes**
- **CP violation: Quark CKM mixing**
- **Non-equilibrium: Possible at the electroweak phase transition.**

Finite Temperature Higgs Potential

$$V_{\mathrm{eff}}^{\mathrm{SM}} = -\, m^2(T)\, H^2 + E_{\mathrm{SM}}\, T\, H^3 + \lambda(T)\, H^4$$

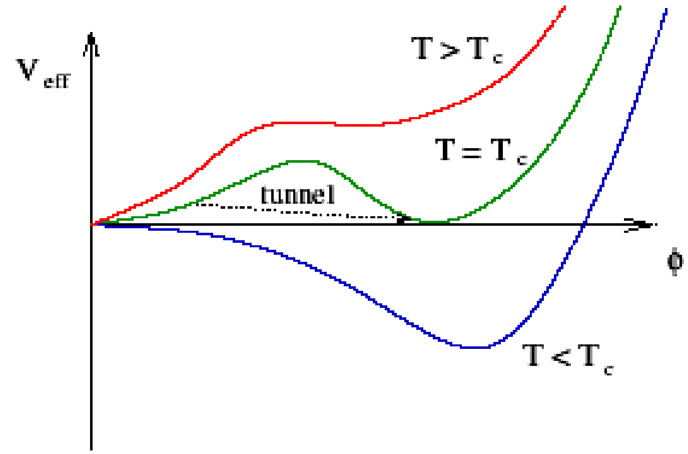
a cubic term is induced, proportional to the sum of the cube of all light boson particle masses

$$-\sum_b \frac{m_b^3(\mathrm{H})}{12\pi}\mathrm{T} \quad \text{with} \quad m_b^2(\mathrm{H}) \approx g_{bH}^2 \mathrm{H}^2$$

In general: $\mathrm{m}_{\mathrm{b}}^2(\mathrm{H},\mathrm{T}) = m_b^2 + g_{bH}^2 \mathrm{H}^2 + \Pi(\mathrm{T})$ which can spoil the behaviour of the cubic term therefore jeopardizing first order phase transition

In the SM the only contribution comes from the transversal components of the gauge bosons

$$E_{SM} \approx \frac{2}{3}\left(\frac{2M_W^3 + M_z^3}{\sqrt{2}\pi\, v^3}\right)$$



→ hence a first order first transition occurs

$$\frac{v(T_c)}{T_c} \approx \frac{\sqrt{2}\,E}{\lambda} \quad , \quad \text{with} \quad \lambda \propto \frac{m_H^2}{v^2}$$

the quartic coupling is proportional to the square of the Higgs mass

$$\frac{v(T_c)}{T_c} > 1 \quad \text{implies} \quad m_H < 40\ \text{GeV} \Rightarrow \ \text{ruled out by LEP!}$$

- **Independent Problem: not enough CP violation**

Electroweak Baryogenesis in the SM is ruled out

Light Stop Effects on Electroweak Baryogenesis

The left- and right-handed stops mix:

$$M_{\tilde{t}}^2 = \begin{bmatrix} m_Q^2 + m_t^2 + D_L & m_t X_t \\ m_t X_t & m_U^2 + m_t^2 + D_R \end{bmatrix}$$

with $\mathrm{X_t} = A_t - \dfrac{\mu^*}{\tan\beta}$

and $\mathrm{m_t} = h_t\,\mathrm{H_2} = h_t \sin\beta\ \phi$

Hierarchy in soft SUSY breaking param:

$\mathrm{m_Q^2} >> \mathrm{m_U^2}$ $\Rightarrow$ best fit to precision electroweak data

The lightest stop $\Rightarrow$ $\mathrm{m_{\tilde{t}}^2(T=0)} \approx \mathrm{m_U^2} + \mathrm{D^2{}_R} + \mathrm{m_t^2}\left(1 - \dfrac{X_t^2}{\mathrm{m_Q^2}}\right)$

has six degrees of freeedom and a coupling of order one to the Higgs

$$V_{eff}^{MSSM} = -m^2(\mathrm{T})\ \phi^2 - \mathrm{T}\left[\mathrm{E_{SM}}\phi^3 + 2N_c \frac{(\mathrm{m_{\tilde{t}}^2} + \Pi_R(T))^{3/2}}{12\,\pi}\right] + \frac{\lambda(T)}{2}\phi^4$$

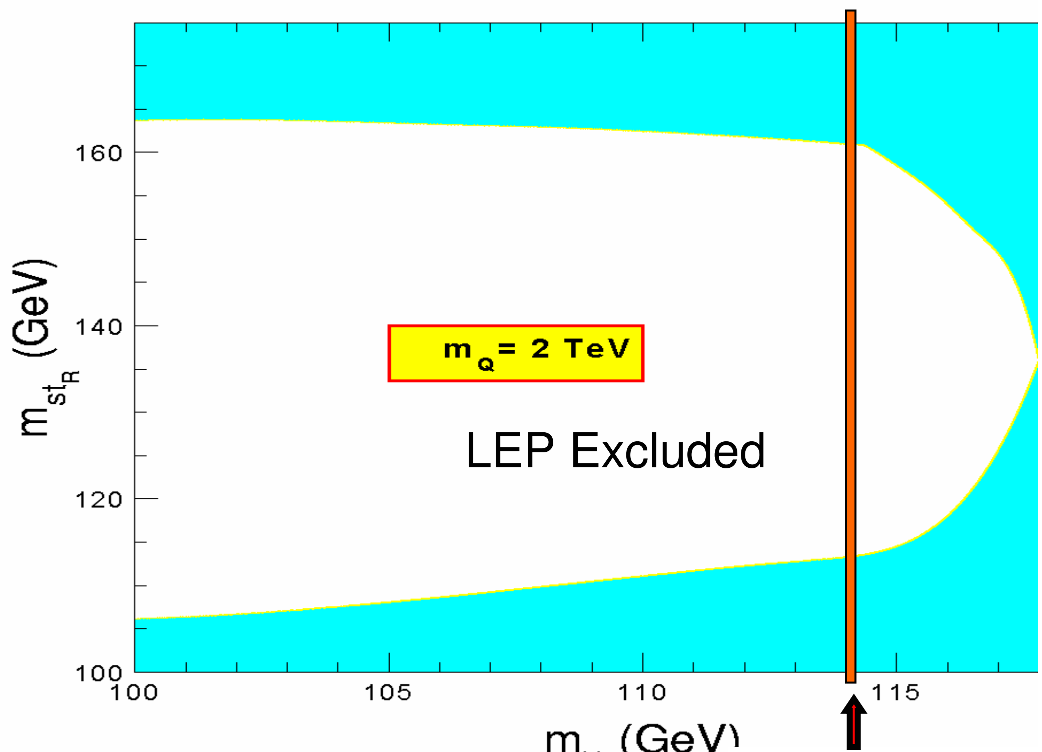
No stop contrib. to cubic term unless $\mathrm{m_U^2} + \Pi_R(T) \approx 0$, very light right-h. stop!

In the MSSM:

$$\mathrm{E_{MSSM}} \approx \mathrm{E_{SM}} + \frac{h_t^3 \sin^3\beta}{2\pi}\left(1 - \frac{X_t^2}{m_Q^2}\right)^{3/2}$$

- **one stop should be quite light, ligther that the top quark and the stop mixing moderate to enhance E**

- **For small stop mixing:** $\mathrm{E_{MSSM}} \approx 9\,\mathrm{E_{SM}} \Rightarrow \mathrm{m^{max.}_{h_{MSSM}}} \approx 3\mathrm{m^{max.}_{H_{SM}}} \approx 120\,\mathrm{GeV}$



M.C, Quiros, Wagner

Present LEP bounds on the SM- like Higgs mass $m_{H_{SM-like}} > 114.6\,\mathrm{GeV}$

Higgs and Stop mass constraints for Electroweak Baryogenesis

- New bosonic degrees of freedom: superpartners of the top quark, with strong couplings to the Higgs. $\Rightarrow E_{SUSY} \approx 8\, E_{SM}$

- ***Higgs masses up to 120 GeV***

- ***The lightest stop must have a mass below the top quark mass.***

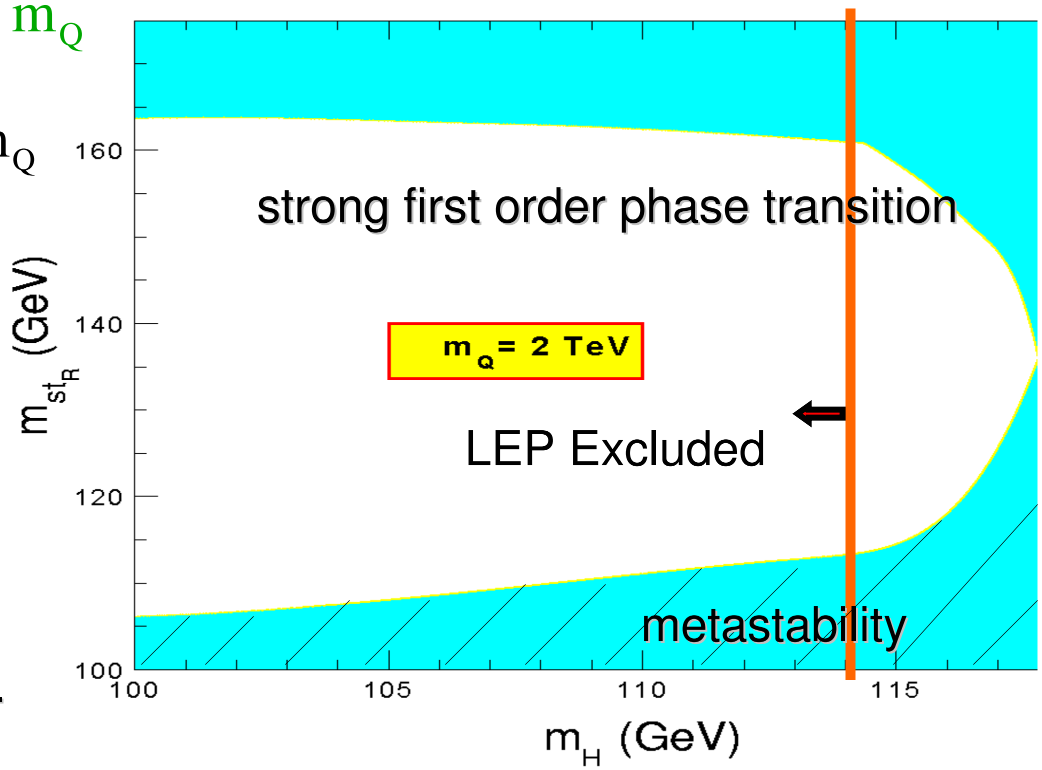
A same point in this plane corresponds to different values of the Higgs and stop param.: $\tan\beta,\ \mathrm{X_t},\ \mathrm{m_U}$ and $\mathrm{m_Q}$

$\tan\beta \geq 5,\ \mathrm{m}_Q \geq 1\,\mathrm{TeV}, \mathrm{X_t} \geq 0.3\,\mathrm{m_Q}$

⇒ lower values lead to too small Higgs mass

$m_U \approx 0, \quad \mathrm{X_t} \leq 0.5\,\mathrm{m_Q}$

⇒ to have a sufficiently strong first order first transition



conditions on the stop sector param. secure vacuum stability ⤻ No color breaking minima

M.C, Quiros, Wagner

In the MSSM: $$E_{MSSM} \approx E_{SM} + \frac{h_t^3 \sin^3\beta}{2\pi}\left(1 - \frac{X_t^2}{m_Q^2}\right)^{3/2}$$

one stop should be quite light and the stop mixing moderate to enhance E_{MSSM}

- For small stop mixing: $E_{MSSM} \approx 9\, E_{SM}$ hence $m_{h_{MSSM}}^{max.} \approx 3 m_{H_{SM}}^{max.} \approx 120\,\mathrm{GeV}$

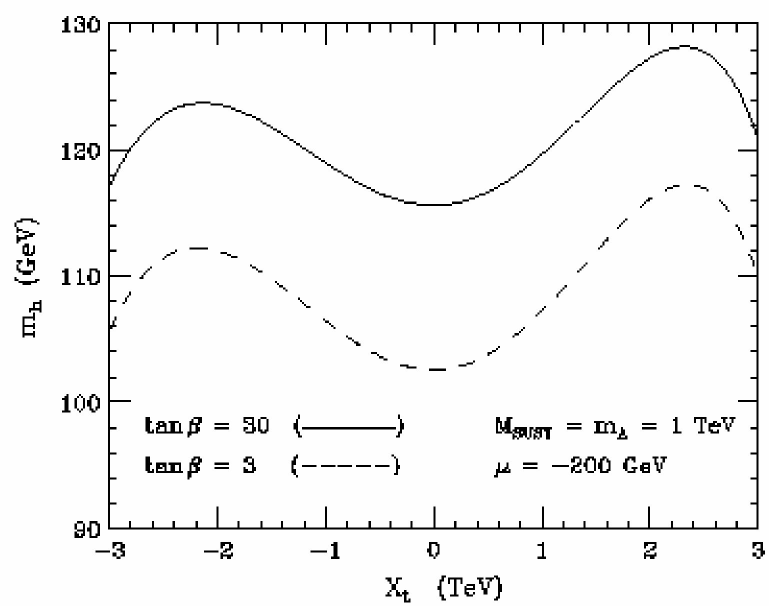
it can work!!

Present LEP bounds on the SM- like Higgs mass imply extra demands!

$$m_{H_{SM-like}} > 114.6\,\mathrm{GeV}$$

- MSSM lightest Higgs mass depends crucialy on m_t^4, on the stop mixing X_t and logarithmically on the stop masses

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3 m_t^4}{8\pi^2 v^2}\left[\log\left(\frac{m_{\tilde{t}_l}^2 m_{\tilde{t}_H}^2}{m_t^4}\right) + 2\frac{|X_t|^2}{m_Q^2}\log\left(\frac{m_{\tilde{t}_H}^2}{m_{\tilde{t}_l}^2}\right) + \vartheta\left(\frac{|X_t|^4}{m_Q^4}\right)\right]$$



hence $m_Q \geq 1\,\mathrm{TeV}$ and $X_t \geq 0.3 m_Q$ needed

Computation of the baryon asymmetry

New CP violating phases in the stop and chargino sector are crucial
[for large values of m_Q, only the chargino –neutralino currents are relevant]

- Interaction with varying Higgs background in the bubble wall creates net neutral and charged Higgsino currents through CP-violating interactions

- Higgsino interactions with plasma creates an excess of left-handed anti-baryons (right-handed baryons)

- Left-handed baryon asymmetry is partially converted to lepton asymmetry via anomalous processes (weak sphalerons: net B violation)

- Baryon asymmetry diffuses into broken phase and gets frozen there since $v(T) / T > 1$

Assuming time relaxation of charge is large (no particle decays)

1. compute CP-violating currents
2. solve diffusion equations describing the above processes

Dependence of the Baryon asymmetry on SUSY parameters

Higgs sector : $\tan\beta,\ m_A$
Chargino sector : mass param. $\mu,\ M_2$ with physical phase $\arg(\mu^* M_2)$

currents proportional to sin($\arg(\mu^* M_2)$), with resonant behavior for $M_2 \approx |\mu|$

Total Baryon asymmetry depends on two contributions proportional to:

★ $\varepsilon_{ij} H_i \partial_\mu H_j = v^2(T)\,\partial_\mu \beta$

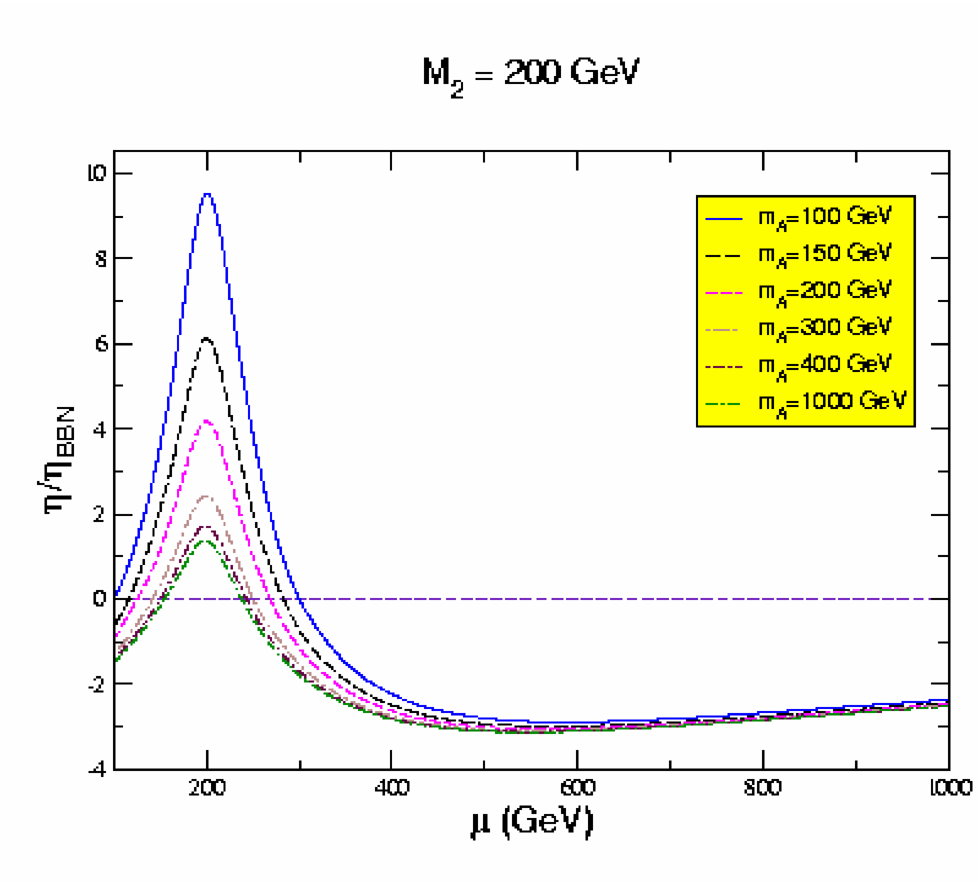
suppressed for large m_A and $\tan\beta$ due to $\Delta\beta$ dependence

★ $H_1 \partial_\mu H_2 + H_2 \partial_\mu H_1 = v^2 \cos(2\beta)\,\partial_\mu \beta + v\,\partial_\mu v \sin(2\beta)$

unsuppressed for large CP-odd masses

Baryon Asymmetry Dependence on the Chargino Mass Parameters

M.Carena, M.Quiros, M. Seco and C.W. '02



Gaugino and Higgsino masses of the order of the weak scale highly preferred

Results for maximal CP violation

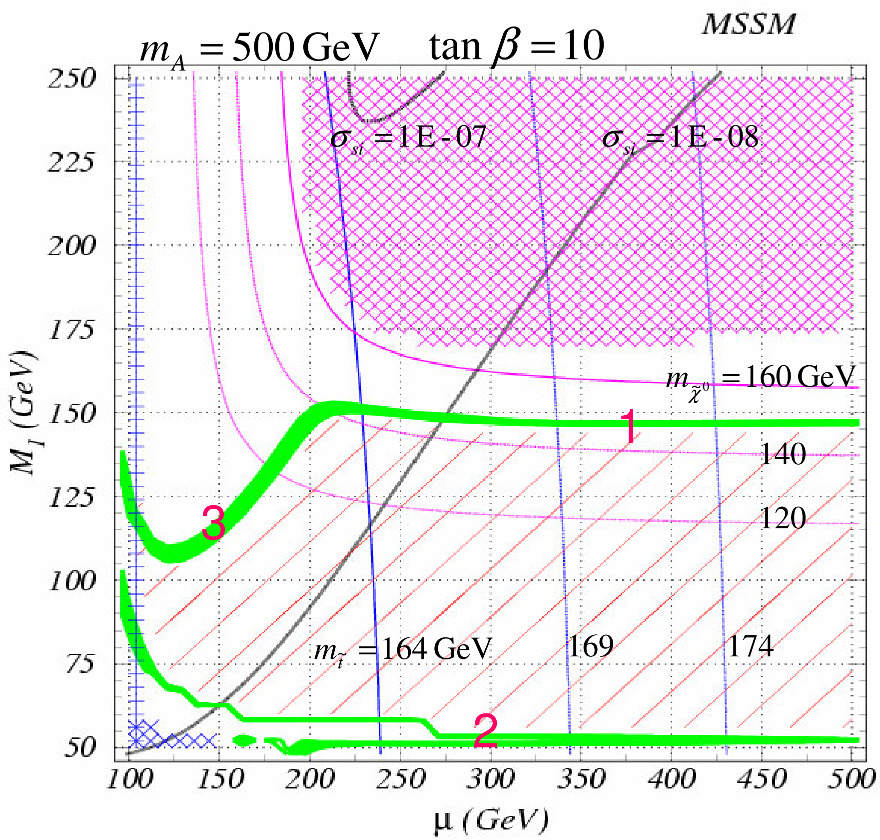
$$\sin(\arg(\mu^* M_2)) = 1$$

Baryon Asymmetry Enhanced for** ;* $M_2 = |\mu|$ ***and smaller values of m_A

Even for large values of the CP-odd Higgs mass, acceptable values obtained for phases of order one.

Dark Matter and Electroweak Baryogenesis

- light right handed stop: $m_{\tilde{U}_3} \approx 0$
- heavy left handed stop: $m_{\tilde{Q}_3} \geq 1\,\mathrm{TeV}$
- values of stop mixing compatible with Higgs mass constraints and with a strong first order phase transition: $X_t = \mu / \tan\beta - A_t = 0.3 - 0.5\, \mathrm{m}_{\tilde{Q}_3}$
- the rest of the squarks, sleptons and gluinos order TeV and $\mathrm{M}_2 \cong 2\mathrm{M}_1$



three interesting regions with neutralino relic density compatible with WMAP obs.
$0.095 < \Omega_{\mathrm{CDM}} h^2 < 0.129$ (green areas)

1. neutralino-stop co-annihilation: mass difference about 20-30 GeV

2. s-channel neutralino annihilation via lightest CP-even Higgs

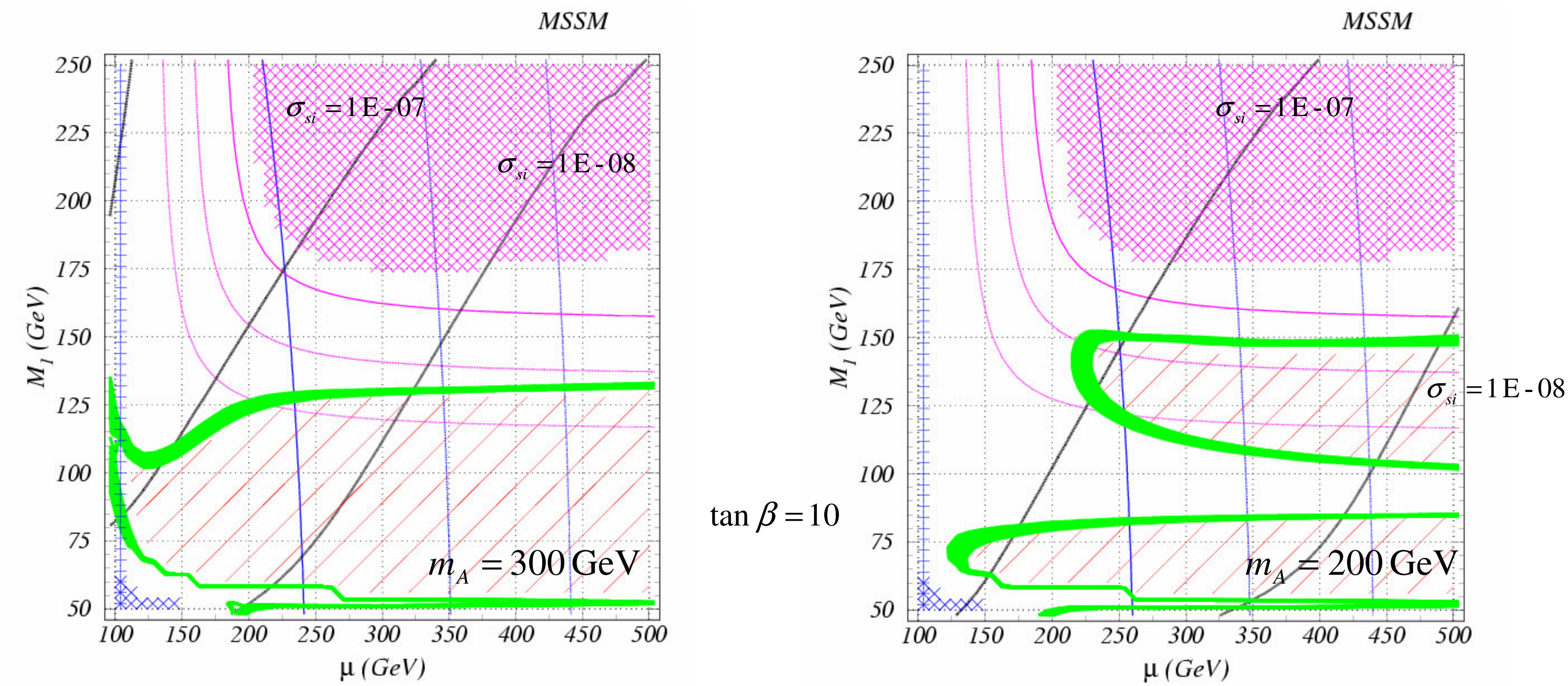
3. annihilation via Z boson exchange
small μ and M_1

Balazs, MC, Wagner 04

Heavy Higgs mass Effects

A,H contribute to annihilation cross section vis s-channel:

- $m_A = 300\,\mathrm{GeV}$ main effect for values of neutralino mass close to stop mass, allowed region moves away from co-annihilation to lower neutralino masses
- $m_A = 200\,\mathrm{GeV}$ new resonant region due to A,H s-channel (much wider band than for h due to $\tan\beta$ enhanced bb couplings). Stop co-annihilation region reappears.



- larger neutralino-proton scattering cross sections!

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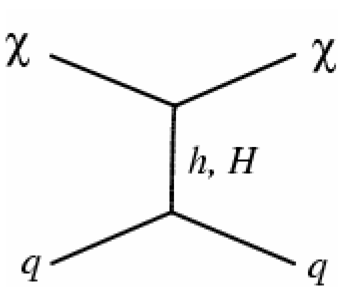
Direct Dark Matter Detection

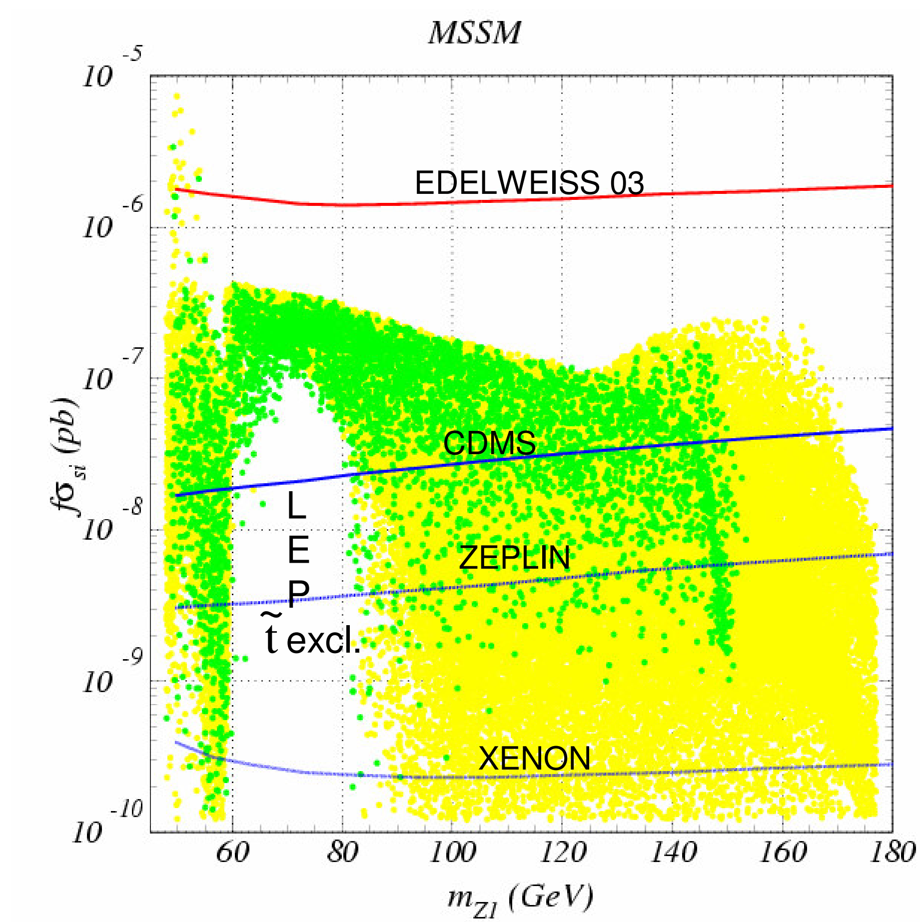
$\not{E}_T$ at colliders ⟶ important evidence of DM candidate,
but, stability of LSP on DM time scales cannot be chekced at colliders

Neutralino DM is searched for in neutralino-nucleon scattering exp. detecting elastic recoil off nuclei



⟶ upper bounds on Spin independent cross sections

Next few years: $\sigma_{SI} \approx 10^{-8}\,\mathrm{pb}$
Ultimate goal: $\sigma_{SI} \approx 10^{-10}\,\mathrm{pb}$



small σ_{si} for large μ : co-annihilation and h-resonant regions

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